



PARAMETERIZING OVERWATER FRICTION VELOCITY AND SEA-SURFACE DRIFT CURRENT USING WAVE STEEPNESS

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Abstract

Overwater friction velocity (U_*) is a vital parameter in air-sea interaction, particularly for the momentum transfer across the air-sea interface including the generation of waves and drift currents (U_{sea}). From operational viewpoints of geophysical fluid mechanics and dynamics such as the analysis and prediction of oil spill trajectory, U_{sea} is an important parameter. In order to understand the characteristics of U_* and U_{sea} , both wind speed (U_{10} at height of 10

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meters) and wave parameters including the dimensionless wave steepness (H_s/L_p , here H_s is the significant wave height, $L_p(= 1.56 T_p^2)$ is the dominant wave length and T_p is the dominant wave period) must be taken into account. However, only few direct simultaneous measurements of all 4 parameters, U_{10} , U_* , H_s and T_p are available in the literature, particularly during tropical cyclones (TCs). In this paper, based on wave data for H_s/L_p and indirect estimation of normalized friction velocity U_*/U_{10} , during Hurricanes Katrina, Ivan, and other TCs, it is found that $U_*/U_{10} = 1.1 H_s/L_p + 0.013$ and $U_{\text{sea}}/U_{10} = 0.53(1.1 H_s/L_p + 0.013)$. The proposed explicit relation between the normalized friction velocity and the wave steepness is verified by both the direct measurements during the Southern Ocean Waves Experiment and the independent wind gust or turbulence intensity method during 6 hurricanes. The explicit relation between the normalized surface current and the wave steepness is validated by the direct measurements during Hurricane Ivan.

Introduction

Understanding and estimation of overwater friction velocity, U_* , and sea-surface drift currents, U_{sea} , are important since they play a crucial role in transporting heat, mass, and momentum across the atmosphere and ocean, significantly influencing global climate, marine ecosystems, oil spills mitigation, and shipping, see, e.g., Knauss [11], Edson et al. [5], and Brink [2]. While the Coriolis force, astronomical tides (the tidal currents), landforms and sea-bed characteristics and bathymetry all impact these surface currents, Wu ([16], equation (2)) stated that both U_* and U_{sea} are related that

$$U_{\text{sea}} = 0.53U_*. \quad (1)$$

All units are in SI.

More recently, Polnikov et al. [13] suggested that U_{sea} is also related to the wave characteristics such as wave steepness but did not provide a specific relation between them. For practical applications in fluid mechanics such as oil spill trajectory analysis (see, e.g., van der Mheen [12]), it is the purpose of this article to investigate the relation between U_{sea} and the wave steepness, H_s/L_p , here H_s is the significant wave height and $L_p (= 1.56 T_p^2$, see e.g., Hsu et al. [8]) is the dominant wave length and T_p is the dominant wave period. Note that both H_s and T_p are measured routinely, e.g., by the National Data Buoy Center (NDBC) (see www.ndbc.noaa.gov) and by the Coastal Data Information Program (CDIP, see [CDIP About](#)) by the Scripps Institution of Oceanography.

Methods

In order to investigate the relation between the drift current and wave characteristics, one needs to first parameterize the relation between U_* and the wind speed at the reference height of 10 meters, U_{10} . This is accomplished as follows:

In the marine atmospheric boundary layer, under near-neutral stability conditions, the logarithmic wind-profile law is valid, see e.g., Hsu [7] that

$$U_{10} = (U_*/k) \ln(10/Z_o). \quad (2)$$

Here $k (= 0.4)$ is the von Karman constant and Z_o is the aerodynamic roughness length.

According to Taylor and Yelland [14],

$$Z_o/H_s = 1200 (H_s/L_p)^{4.5}. \quad (3)$$

Now, based on Csanady ([3], p.68, equation 2.14),

$$U_* = 27 H_s^2 / T_p^3 \quad (4)$$

And following Hsu et al. ([8], equation (8)) that

$$U_{10} = 35 H_s / T_p. \quad (5)$$

From equations (4) and (5) and the definition of L_p , we have

$$U_* / U_{10} = 1.2 H_s / L_p. \quad (6)$$

Because equations (4) and (5) are based on limited datasets, more measurements are required to further substantiate equation (6). However, since all field datasets require statistical analysis, equation (6) needs to be consistent with the general linear regression formula so that

$$U_* / U_{10} = a H_s / L_p + b. \quad (7)$$

Here the coefficients “ a ” and “ b ” need to be determined from field measurements. Note that, from the viewpoint of geophysical fluid dynamics, coefficient “ b ” is needed to account for the effects of capillary waves induced by the surface tension when the wind waves are absent. In addition, the sea surface seldom stays in a perfect still or calm condition because some background swell may be present.

Before the results are presented, following criteria are employed for our data analysis: they are (1) according to Drennan et al. [4], a wind sea starts when $H_s / L_p \geq 0.020$; (2) Following Edson et al. [5], when $U_{10} > 8.5 \text{ ms}^{-1}$, sea surfaces are considered fully rough; and (3) To ensure the atmospheric stability is near-neutral, the criterion presented in Hsu ([6] Figure 1) is utilized.

Results

On the basis of aforementioned analysis and discussion, following datasets are employed as indicated in Figure 1. They are: Hurricane Katrina because of large $H_s = 17 \text{ m}$ as measured at Buoy 42040 by the NDBC;

Hurricane Ivan (H_s up to 18 m) in Teague et al. ([15], Table 4 for Moorings # M3, M4 and M5 but not M6 because the value of T_p was less than other wave period statistics); and another 6 hurricanes as listed in Hwang and Walsh ([10], Table 1). Our result, as presented in Figure 1, indicates that equation (7) becomes

$$U_*/U_{10} = 1.1 H_s/L_p + 0.013, \quad (8)$$

with a very high correlation coefficient, $R = 0.99$.

Note that values of U_*/U_{10} are computed based on equations (2) and (3) for the given pairs of H_s and T_p .

Equation (8) is further verified by an independent dataset from Banner et al. ([1], Table 2) for upwind conditions since $R = 0.88$ and its slope is 1.07, which is within the 10% for field measurements as suggested by the NDBC.

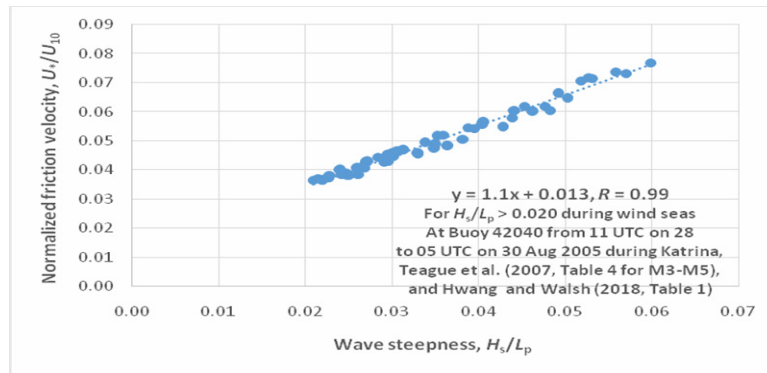


Figure 1. Relation between U_*/U_{10} and H_s/L_p based on the datasets as listed in the figure.

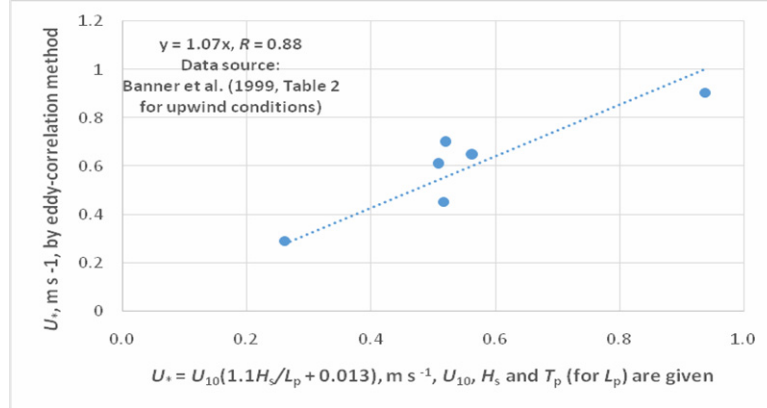


Figure 2. Verification of equation (8) based on an independent dataset, see text.

In order to compare equation (8) against the wind gust or turbulence intensity method as provided in Hsu [7], Figure 3 is presented using the simultaneous measurements of U_{10} , U_{gust} (for wind gust), H_s and T_p as listed in Table 1 during 6 hurricanes. Note that the scatter of the data points might be due to the wind and wave measurements near the “eyes” (where U_{10} was lower and H_s higher) or closer to the radius of max winds (where U_{10} was higher and H_s lower) of hurricanes. Nevertheless, since $R = 0.81$ and the slope is 0.92, which is within the 10% measurement error based on NDBC buoys.

Table 1. Simultaneous measurements of U_{10} , U_{gust} , H_s , and T_p for wind seas during 6 hurricanes based on www.ndbc.noaa.gov

Hurricane name	Month/Year	From	To	NDBC Buoy
Kate	Nov/1985	0200 UTC on 19	2300 UTC on 21	42003
Lili	Oct/2002	2200 UTC on 01	0900 UTC on 03	42001
Ivan	Sep/2004	0800 UTC on 13	1100 UTC on 16	42003
Katrina	AUG/2005	1500 UTC on 26	0500 UTC on 28	42003
Wilma	OCT/2005	1200 UTC on 19	0200 UTC on 24	42056
Ike	Sep/2008	0050 UTC on 10	1350 UTC on 13	42001

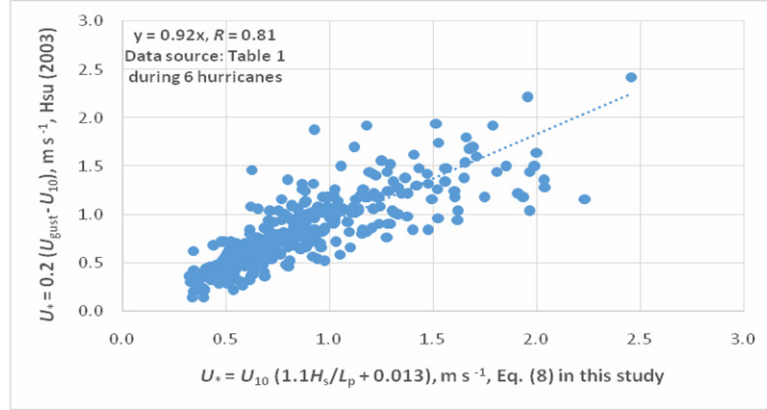


Figure 3. Verification of equation (8) against the wind gust or turbulence intensity method based on Hsu [7] during 6 hurricanes as listed in Table 1.

Finally, we can proceed with the evaluation for the relation between the drift current and wave steepness. By dividing both sides of equation (1) by U_{10} and using equation (8), one gets

$$U_{\text{sea}}/U_{10} = 0.53U_*/U_{10}, \text{ or}$$

$$U_{\text{sea}} = 0.53U_{10}(1.1H_s/L_p + 0.013). \quad (9)$$

Here, following Hsu ([9], equation (12)),

$$U_{10} = 2.33H_s + 6. \quad (10)$$

Based on the datasets provided in Teague et al. ([15], Tables 2 and 4) during Hurricane Ivan, our results are presented in Table 2, indicating that equation (9) may be useful to estimate U_{sea} , e.g., for oil spill trajectory analysis, since the composite ratio of the estimated U_{sea} and those as measured is 0.95. In other words, approximately 95% of the total drift currents may be explained by the combined effects of wind and wave forcing.

Table 2. An evaluation of the formulas based on this study using the datasets from Teague et al. ([15], Tables 2 and 4) during Hurricane Ivan

Mooring	M3	M4	M5	Row Average
H_s , m	18.0	16.1	17.7	17.3
T_p , sec	14.8	13.6	14.8	14.4
H_s/L_p	0.053	0.056	0.052	0.054
U_{sea} , ms^{-1} , measured	1.73	1.96	1.91	1.87
U_{sea} , ms^{-1} , estimated	1.81	1.74	1.75	1.77
U_{10} , ms^{-1} , estimated	48	44	47	46
$U_{sea, est.}/U_{sea, meas.}$	1.05	0.89	0.92	0.95

Conclusions

On the basis of aforementioned analysis and discussion, it is concluded that

(1) The normalized overwater friction velocity (U_*/U_{10}) and the wave steepness (H_s/L_p) are related as $U_*/U_{10} = 1.1 H_s/L_p + 0.013$. The intercept (= 0.013) is needed to account for the capillary waves due to surface tension;

(2) The above relation can reconcile the long suspected notion that when $H_s/L_p \geq 0.02$ for the commencement of the wind seas as suggested in Drennan et al. [4] is also coincided with the onset of the fully rough sea when $U_*/U_{10} = 0.035$ as recommended in Edson et al. [5]; and

(3) The normalized overwater friction velocity (U_*/U_{10}), which is also related to the normalized sea-surface drift current (U_{sea}/U_{10}) so that $U_{sea}/U_{10} = 0.53 U_*/U_{10} = 0.53(1.1 H_s/L_p + 0.013)$ as suggested by Wu [16] is verified during Hurricane Ivan in 2004. This proposed relation may be

employed to explain both effects of wind and waves, which is needed for operational geophysical fluid mechanics such as oil spill trajectory analysis.

References

- [1] M. L. Banner, W. Chen, E. J. Walsh, J. B. Jensen, S. Lee and C. Fandry, The Southern Ocean waves experiment. Part I: Overview and mean results, *Journal of Physical Oceanography* 29 (1999), 2130-2145.
- [2] K. H. Brink, *Physical Oceanography of Continental Shelves*, Princeton University Press, 2023.
- [3] G. T. Csanady, *Air-Sea Interaction: Laws and Mechanisms*, Cambridge University Press, 2001.
- [4] W. M. Drennan, P. K. Taylor and M. J. Yelland, Parameterizing the sea surface roughness, *J. Phys. Oceanogr.* 35 (2005), 835-848. doi:10.1175/JPO2704.1.
- [5] J. B. Edson, V. Jampana, R. A. Weller, S. P. Bigorre, A. J. Plueddemann, C. W. Fairall et al., On the exchange of momentum over the open ocean, *J. Phys. Oceanogr.* 4 (2013), 1589-1610.
- [6] S. A. Hsu, An overwater stability criterion for the offshore and coastal dispersion model, *Boundary-Layer Meteorology* 60 (1992), 397-402.
- [7] S. A. Hsu, Estimating overwater friction velocity and exponent of power-law wind profile from gust factor during storms, *J. Waterway Port Coast Ocean Eng.* 129 (2003), 174-177.
- [8] S. A. Hsu, Y. He and H. Shen, Buoy measurements of wind-wave relations during hurricane Matthew in 2016, *J. Phys. Oceanogr.* 47 (2017), 2603-2609.
- [9] S. A. Hsu, On the relation between overwater friction velocity and the wind speed during tropical cyclones, *Adv. Environ. Eng. Res.* 6(1) (2025), 007. doi:10.21926/aeer.2501007.
- [10] P. A. Hwang and E. J. Walsh, Estimating maximum significant wave height and dominant wave period inside tropical cyclones, *Weather and Forecasting* 33(4) (2018), 955-966. doi:10.1175/WAF-D-17-0186.1.
- [11] J. A. Knauss, *Introduction to Physical Oceanography*, 2nd Edition, Waveland Press, 2005.
- [12] M. van der Mheen, C. Pattiaratchi, S. Cosoli and M. Wandres, Depth-dependent correction for wind-driven drift current in particle tracking applications, *Front. Mar. Sci.* 7 (2020), 305. doi:10.3389/fmars.2020.00305.

- [13] V. Polnikov, F. Qiao and H. Ma, Surface drift currents induced by waves and wind in a large tank, *Journal of Physical Oceanography* 50 (2020), 3063-3073. doi:10.1175/JPO-D-20-0009.1.
- [14] P. K. Taylor and M. J. Yelland, The dependence of sea surface roughness on the height and steepness of the waves, *J. Phys. Oceanogr.* 31 (2001), 572-590.
- [15] W. J. Teague, E. Jarosz, D. W. Wang and D. A. Mitchell, Observed oceanic response over the upper continental slope and outer shelf during Hurricane Ivan, *Journal of Physical Oceanography* 37(9) (2007), 2181-2206. doi.org/10.1175/JPO3115.1.
- [16] J. Wu, Sea-surface drift currents induced by wind and waves, *Journal of Physical Oceanography* 13 (1983), 1441-1451.